PATH-ATTITUDE INCONSONANCE IN HIGH SPEED FLIGHT AND RELATED PATH CONTROL ISSUES

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Abstract

This paper presents results of a joint research effort of NASA Dryden Flight Research Center and the Institute of Flight Mechanics and Flight Control of Technische Universität München on longitudinal flight dynamics at hypersonic speeds.

At high speeds a large time lag between pitch attitude and flight path angle exists. The mechanisms which cause this path-attitude decoupling are described. It will be shown further that an limiting effect exists.

An "aggressive stick" piloting technique to avoid the shortcomings of the path-attitude lag is described. This type of control is also effective to stabilize phugoid.

The simulation facility of Dryden Flight Research Center which was used in the evaluation is described. Simulation results concerning the effect of path-attitude lag on "aggressive stick" technique, of time delay and scaling of vertical speed information are presented. Furthermore results of flight tests with SR-71 and Tu-144 at high supersonic speeds for similar topics are presented.

Nomenclature

$\boldsymbol{A}(s)$	coefficient matrix of homogeneous system
A_γ	factor of flight path transfer function
A_θ	factor of pitch attitude transfer function
$\boldsymbol{B}$	scaling matrix of control inputs
C_D	drag coefficient
C_{DV}	$= \partial C_D / \partial (V/V_0)$
$C_{D\alpha}$	$= \partial C_D / \partial \alpha$
$C_{D\delta}$	$= \partial C_D / \partial \delta_e$
C_L	lift coefficient
C_{LV}	$= \partial C_L / \partial (V/V_0)$
$C_{L\alpha}$	$= \partial C_L / \partial \alpha$
$C_{L\delta}$	$= \partial C_L / \partial \delta_e$
C_m	pitch moment coefficient
C_{m_h}	$= (1/\rho_h)\, \partial C_m / \partial h$
C_{m_q}	$= 2\, \partial C_m / \partial (q \bar{c} / V_0)$
C_{mV}	$= \partial C_m / \partial (V/V_0)$
$C_{m\alpha}$	$= \partial C_m / \partial \alpha$
$C_{m\dot{\alpha}}$	$= 2\, \partial C_m / \partial (\dot{\alpha} \bar{c} / V_0)$
$C_{m\gamma}$	$= \partial C_m / \partial \gamma$
$C_{m\delta}$	$= \partial C_m / \partial \delta_e$
$\bar{c}$	mean aerodynamic chord
g	acceleration due to gravity
h	altitude
i_y	radius of gyration
$KEAS$	knots equivalent airspeed
M	Mach number
m	mass
N_δ^γ	numerator of flight path transfer function

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14. ABSTRACT

This paper presents results of a joint research effort of NASA Dryden Flight Research Center and the Institute of Flight Mechanics and Flight Control of Technische Universität München on longitudinal flight dynamics at hypersonic speeds. At high speeds a large time lag between pitch attitude and flight path angle exists. The mechanisms which cause this path-attitude decoupling are described. It will be shown further that an limiting effect exists. An aggressive stick piloting technique to avoid the shortcomings of the path-attitude lag is described. This type of control is also effective to stabilize phugoid. The simulation facility of Dryden Flight Research Center which was used in the evaluation is described. Simulation results concerning the effect of path-attitude lag on aggressive stick technique, of time delay and scaling of vertical speed information are presented. Furthermore results of flight tests with SR-71 and Tu-144 at high supersonic speeds for similar topics are presented.

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N_{δ}^{θ}	numerator of pitch attitude transfer function
n_h	thrust / altitude dependence, $n_h = (1/\rho_h)\,\partial(T/T_0)/\partial h$
n_V	thrust / speed dependence, $n_V = (V_0/T_0)\,\partial T/\partial V$
S	reference area
s	Laplace operator
T	thrust
T_2	time to double amplitude
T_h	height mode time constant
$T_{\theta 1}$	low frequency pitch attitude zero
$T_{\theta 2}$	high frequency pitch attitude zero
t	time
$\boldsymbol{u}$	control vector
V	speed
$\boldsymbol{x}$	state vector
z_T	vertical thrust line offset
α	angle of attack
γ	flight path angle
Δ	denoting a perturbation, e.g.: ΔV
$\Delta(s)$	denominator of transfer functions
δ_e	pitch control
δ_T	throttle position
ζ_P	phugoid damping ratio
ζ_{SP}	short period damping ratio
ζ_θ	pitch attitude damping ratio
μ	relative mass parameter, $\mu = 2\,m/(\rho_0\, S\, \bar{c})$
θ	pitch attitude
ρ	air density
ρ_h	density gradient, $\rho_h = (1/\rho_0)\,\mathrm{d}\rho\;/\mathrm{d}h$
σ	damping
τ	reference time, $\tau = \mu\,\bar{c}/V_0$
ω	frequency
ω_P	undamped natural phugoid frequency
ω_{SP}	undamped natural short period frequency
ω_θ	undamped natural pitch attitude frequency

1 Introduction

For improving performance and reducing launch costs of space transportation systems a significant interest in aerospace planes which are using aerodynamic lift and air breathing engines exists [1-3]. These vehicles which are capable of sustained hypersonic flight require research for solving many challenging problems.

Besides the fields of aerothermodynamics, propulsion and materials also flight dynamics and associated handling qualities show unique characteristics [4]. This is the result of the integrated airframe/propulsion system which is characteristic for aerospace planes and causes a significant coupling between aerodynamics, propulsion and flight dynamics. Further the high kinetic energy level during hypersonic flight and altitude dependencies have a substantial effect [5].

Flight path control is among the unique problems of hypersonic flight dynamics. In subsonic flight the delay between pitch attitude and flight path after a stick input is small, usually below 2 seconds. Thus the pilot can substitute one for the other. In the high speed regime a large time lag of 20 seconds or more [6] exists between the pitch attitude change following an elevator input and the associated flight path response. This reaction will be referred to as path-attitude decoupling or inconsonance.

Different aspects of the path-attitude decoupling problem are subject of theoretical and experimental research [6-11]. The difficulty is considered to be associated with the high speed [6] and low lift curve slope [7] typical for vehicles capable of hypersonic flight. Another reason is a low frequency washout characteristic due to altitude effects [8]. Further flight controllers using direct lift control have been evaluated [9].

2 Dynamics of Hypersonic Flight

2.1 Equations of Motion

At hypersonic speeds altitude dependant forces and moments are significant [5] and must be taken into account just as engine effects [12].

The equations of motion in the hypersonic speed regime may be described as

$$\boldsymbol{A}(s)\,\dot{\boldsymbol{x}}(s) = \boldsymbol{B}\,\boldsymbol{u}(s) \qquad (1)$$

where

$$\boldsymbol{A}(s)=\left[\begin{array}{c:c:c} \begin{array}{c} s\,\tau \\ +(2-n_V)\,C_D+C_{DV} \end{array} & C_{D\alpha} & \begin{array}{c} s\,\tau\,\dfrac{\tau\,g_0}{V_0} \\ +\mu\,\bar{c}\,\rho_h\,C_D\,(1-n_h) \end{array} \\ \hdashline 2\,C_L+C_{LV} & C_{L\alpha}+C_D & -(s\,\tau)^2+\mu\,\bar{c}\,\rho_h\,C_L \\ \hdashline \mu\,C_{mV} & \begin{array}{l} -(s\,\tau)^2\,(i_y/\bar{c})^2 \\ +s\,\tau\,(C_{m_q}+C_{m_{\dot\alpha}}) \\ +\mu\,C_{m_\alpha} \end{array} & \begin{array}{l} -(s\,\tau)^3\,(i_y/\bar{c})^2 \\ +(s\,\tau)^2\,C_{m_q}+s\,\tau\,\mu\,C_{m_\gamma} \\ +\mu^2\,\bar{c}\,\rho_h\,C_{mh} \end{array} \end{array}\right] \qquad (2)$$

$$\boldsymbol{x}(s)=\left[\Delta V/V_0,\ \Delta\alpha,\ \Delta h/(\mu\,\bar{c})\right]^T \qquad (3)$$

$$\boldsymbol{B}=-\left[\begin{array}{c:c} C_{D\delta} & -C_D \\ \hdashline C_{L\delta} & 0 \\ \hdashline \mu\,C_{m\delta} & \mu\,(z_T/\bar{c})\,C_D \end{array}\right] \qquad (4)$$

$$\boldsymbol{u}(s)=\left[\delta_e,\ \delta_T\right]^T \qquad (5)$$

The short term dynamics show similar dependencies as in the subsonic speed regime. The long term dynamics however have unique characteristics which manifests in phugoid and height mode. The following approximations apply:

- Phugoid:

$$\omega_p^2\approx -g\,\rho_h \qquad (6)$$

$$\zeta_p\approx 0 \qquad (7)$$

- Height mode:

$$\frac{1}{T_h}\approx\left[2\,n_h-n_V\right]\frac{C_D}{C_L}\,\frac{g}{V_0} \qquad (8)$$

2.2 Path-Attitude Decoupling

As shown in Fig. 1 the time delay between pitch attitude and flight path following an elevator step input in the subsonic speed regime is rather small (c. 1s). At hypersonic speeds however a large time lag of 20 seconds or more exists between pitch attitude and flight path response

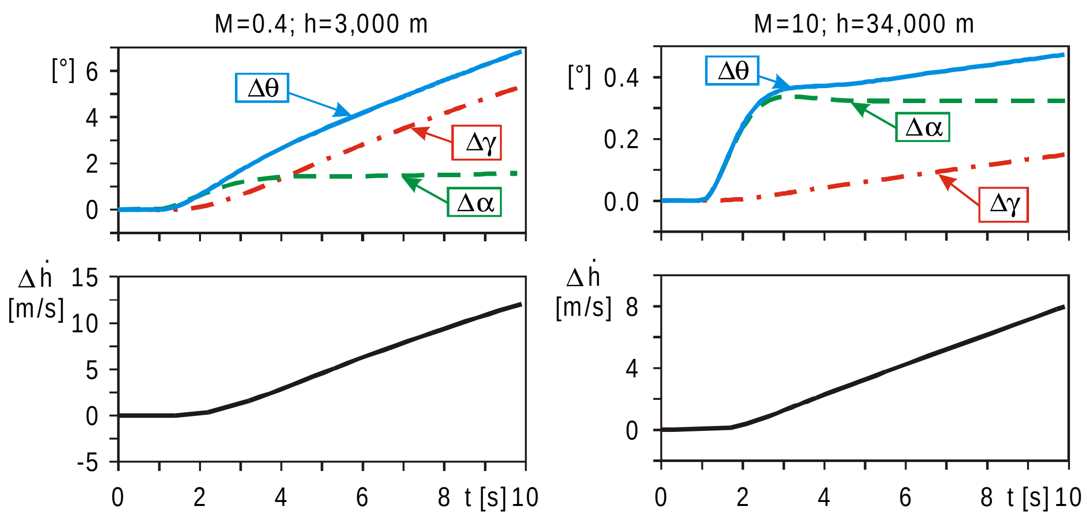

Fig. 1 Time histories for a pitch step input (-1° at 1 s) for subsonic (M=0.4, h=3,000 m) and hypersonic (GHAME model, M=10, h=34,000 m) flight

which is referred to as path-attitude decoupling. The changes of the angles concerned are much smaller in hypersonic flight than in the conventional speed regime. Despite this the resulting vertical speed however is of the same order of magnitude in both cases.

The path-attitude decoupling effect also manifests in the corresponding transfer functions which for the frequency range of interest may be expressed as

$$\frac{\gamma(s)}{\delta_e(s)} = \frac{N_\delta^\gamma(s)}{\Delta(s)} = \frac{A_\gamma s}{\Delta(s)} \tag{9}$$

$$\frac{\theta(s)}{\delta_e(s)} = \frac{N_\delta^\theta(s)}{\Delta(s)} = \frac{A_\theta\ (s+1/T_{\theta_1})\,(s+1/T_{\theta_2})}{\Delta(s)} \tag{10}$$

where

$$\Delta(s) = (s^2 + 2\,\zeta_{sp}\ \omega_{sp}\ s + \omega_{sp}^2)(s^2 + 2\,\zeta_p\ \omega_p\ s + \omega_p^2)$$

The numerator zero $T_{\theta 1}$ shows different dependencies compared with the subsonic case. It may be expressed as:

$$T_{\theta_1} \approx -\frac{C_{L\alpha}/C_L}{V_0\ \rho_h} \tag{11}$$

The other zero $T_{\theta 2}$ however is similar to the subsonic case:

$$T_{\theta_2} \approx \frac{V_0}{g}\ \frac{C_L}{C_{L\alpha}} \tag{12}$$

As shown in Fig. 2 both zeros move with increasing airspeed towards each other and combine to complex zeros yielding

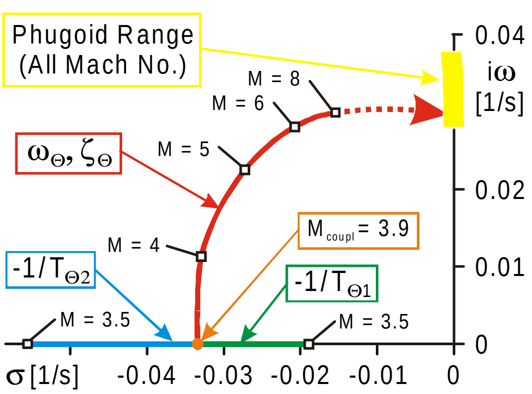

Fig. 2 Effect of Mach number on attitude numerator zeros (GHAME model, maximum lift-to-drag ratio)

$$N_\delta^\theta(s) = A_\theta\,(s^2 + 2\,\zeta_\theta\ \omega_\theta\ s + \omega_\theta^2) \tag{13}$$

where

$$\omega_\theta^2 \approx -g\ \rho_h \tag{14}$$

$$\zeta_\theta \approx \frac{1}{2\,V_0}\ \frac{C_{L\alpha}}{C_L}\ \sqrt{-\frac{g}{\rho_h}} \tag{15}$$

There is no aerodynamic or speed effect on ω_θ and it is also similar to the phugoid frequency (6). At higher velocities the damping ratio ζ_θ converges towards zero. Therefore at higher Mach numbers a pole zero compensation between the complex pitch attitude zeros and the phugoid exists.

The described characteristics of the pitch attitude zeros results in an upper limit for the delay between path and attitude changes at a high level.

Fig. 3 depicts frequency responses for pitch attitude and flight path. Pitch attitude has a different shape than in the conventional speed regime and is flat at frequencies between ω_P and ω_{SP}, corresponding with path-attitude decoupling. Flight path angle has a similar shape as at subsonic speeds but a lower amplitude. The region between ω_P and ω_{SP} shows a K/s characteristic.

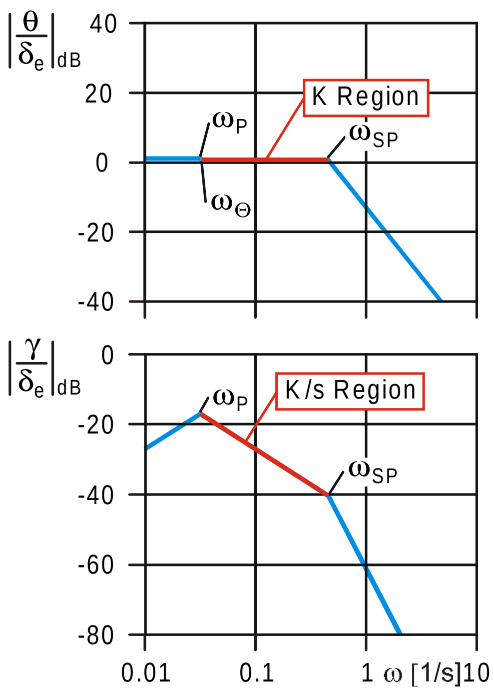

Fig. 3 Asymptotic Bode plots for pitch attitude and flight path angle transfer functions (GHAME model, M=10, h=110,000 ft)

2.3 Flight Path Control Technique

For manual control tasks an open-loop *K/s* characteristic in the frequency range of concern is preferable [13]. As shown in Fig. 3 the flight path angle response has such a shape. Therefore it may be used as reference for flight path control by the pilot.

Since

$$\dot{h} = V \sin \gamma \tag{16}$$

vertical speed control is an equivalent reference for flight path control with speed approximately constant. This technique was investigated in simulator experiments. It was described as "aggressive stick" by the involved pilots. A similar vertical speed feedback piloting technique was also used for flying the SR-71 [11]. The piloting technique in mind is described in more detail in [14].

Fig. 4 presents a comparison between the "aggressive stick" and a conventional pitch control technique. The vertical speed deviations with the "aggressive stick" control technique are much smaller than those of the other case. There is also a significant difference in the Cooper-Harper rating in favor of the "aggressive stick" technique (4 vs. 7 in the other case).

Fig. 5 shows flight test results for a horizontal turn maneuver during supersonic cruise with pitch attitude (Tu-144) and vertical speed

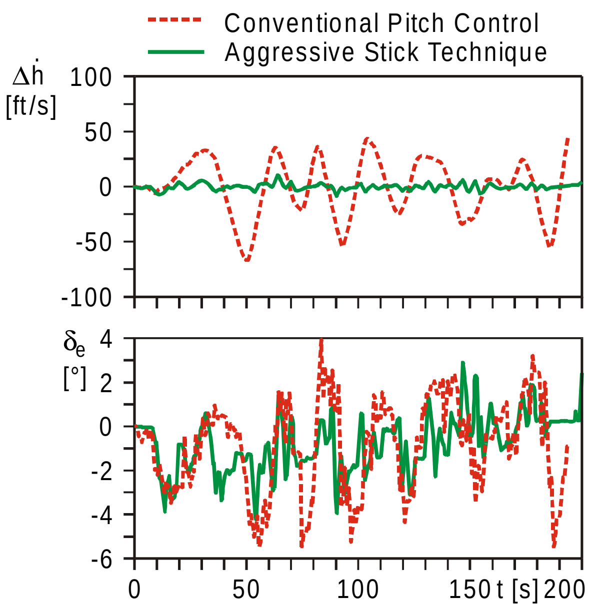

Fig. 4 Comparison of conventional and aggressive stick piloting techniques (GHAME model, M=10, h=110,000 ft)

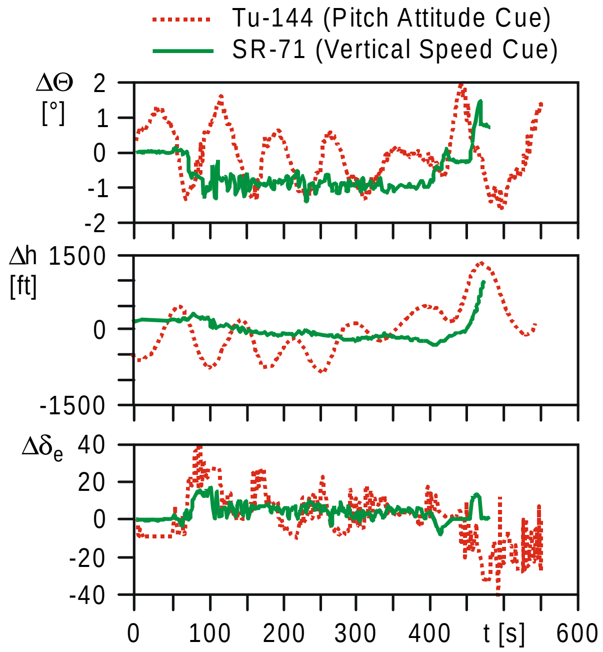

Fig. 5 Comparison of different pilot cues for horizontal turn task maneuvers during supersonic cruise

(SR-71) cues for the pilot. Altitude and pitch attitude deviations with vertical speed control technique are much smaller than those with conventional pitch attitude control. This is similar to the hypersonic results (Fig. 4).

An additional advantage of the above flight path control technique is a stabilization of the marginally stable phugoid. This is shown in Fig. 6 which presents the effect of the flight path angle feedback on phugoid and height mode.

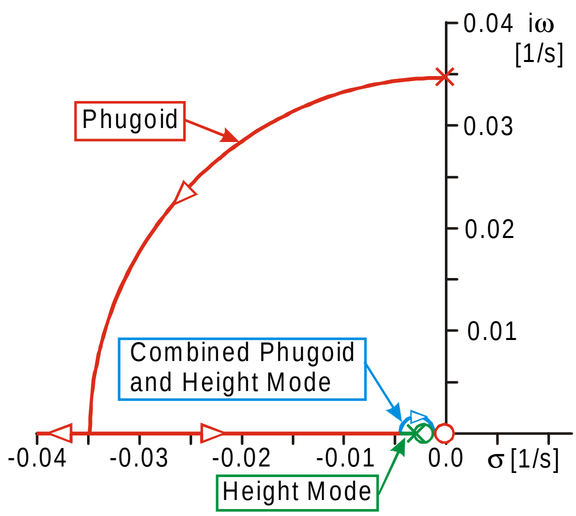

Fig. 6 Effect of flight path feedback to elevator (GHAME model, M=10, h=110,000 ft)

3 Simulator Experiments

3.1 Simulation Facility

For the evaluation a fixed base simulator of the Dryden Flight Research Center with conventional stick, rudder and throttle controls was used (Fig. 7). Stick and rudder pedals are trimable and the associated forces are electrically generated. A Space Shuttle type instrumentation panel is installed in the simulator. For the experiments a customized simulated head up display was used.

Test pilots of NASA Dryden Flight Research Center with a large experience in high speed flight conducted the evaluation.

3.2 Simulation Model

For simulating a hypersonic vehicle the GHAME program [15] was used. It comprises aerothermodynamic and engine models of a generic single stage aerospace plane from start to orbit (0 • M • 25). The six degree of freedom equations of motion include effects of an oblate and rotating earth.

Level I short period handling qualities [16] have been realized with an appropriate pitch damper.

3.3 Simulated Head Up Display

The simulated head up display (Fig. 8) was customized for hypersonic cruise tasks.

In the center of the display is a high resolution pitch ladder moving around a fixed symbol (═╱╲╱═). Additional information on the pitch ladder concerns a high resolution vertical speed indicator (diamond symbol ◇). Furthermore, path and sideslip angle are presented (airplane symbol). Other scales indicate longitudinal and vertical acceleration as well as speed, altitude, bank angle and heading. A more detailed description is included in reference [17].

3.4 Atmospheric Disturbances

During Space Shuttle flights density changes at constant altitude have been observed [18]. In accordance to those observations density perturbations of (1-cos) type have been implemented with a maximum amplitude of 2.5 % of the actual density and a duration of 20 seconds. The sign and interval between the perturbations is selected by random.

3.5 Maneuver

The following representative maneuvers for hypersonic cruise tasks have been specified with corresponding performance limits:

- Horizontal turn: The task is to perform a heading change of 12° with constant equivalent airspeed and altitude followed by a flight at the final heading with constant speed and altitude for 1 minute (Table 1).
- Vertical plane altitude change : The task is to perform an altitude change of 3,000 ft with 2,000 ft/min vertical speed, followed by a flight at constant altitude and speed for 1 minute (Table 2).

Fig. 7 Cockpit of the civil transport simulator used during evaluations

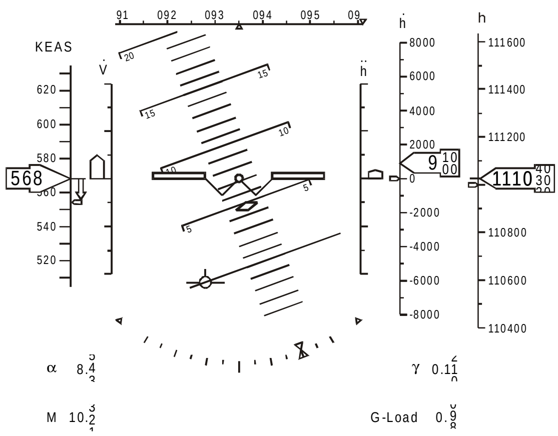

Fig. 8 Simulated head up display used during evaluations

Controlled Parameters	Adequate Performance	Desired Performance
Target Heading	±1°	±0.5°
Target Altitude	±600 ft	±300 ft
Trim Speed (EAS)	±10 kt	±5 kt

Table 1 Controlled parameters and performance values for horizontal turn

Controlled Parameters	Adequate Performance	Desired Performance
Target Altitude	±600 ft	±300 ft
Trim Speed (EAS)	±10 kt	±5 kt

Table 2 Controlled parameters and performance values for vertical plane altitude change

Similar maneuvers were specified for flight tests with the SR-71 [11].

After each simulation run the test pilot answered a questionnaire and gave a Cooper-Harper rating [19].

4 Flight Tests

Dryden Flight Research Center operates SR-71 research airplanes (Fig. 9) capable of sustained flight at Mach 3+ in altitudes above 80,000 feet. With these aircraft's flight tests for similar topics as considered in this article have been performed [11].

In the high supersonic speed regime at which the SR-71 operates flight dynamics similarities with respect to hypersonics exist. For example there is already a path attitude lag of 4 to 5 seconds at Mach 3 so that an alternate vertical speed feedback control technique was considered [11].

Fig. 9 Research aircraft SR-71 operated by Dryden Flight Research Center

5 Handling Qualities Results

During the simulation evaluations the short term dynamics were kept within Level I [16] limits.

5.1 Path-Attitude Lag Variation

Simulation experiments for aircraft configurations with different path-attitude lags were performed using the "aggressive stick" piloting technique for controlling flight path.

Handling qualities ratings for different path-attitude delays and two maneuvers are presented in Fig. 10. Despite the large variation of path attitude lag there are only small changes. Vertical plane altitude change maneuvers are rated better than the horizontal turn.

Similar results have been obtained at flight test with the SR-71 research airplane at high supersonic speeds (Fig. 10).

5.2 Effect of Vertical Speed Information

The "aggressive stick" technique as described above requires a precise indication of $\dot{h}$ with a high resolution and in an adequate format. This was done with the diamond symbol moving along the pitch ladder.

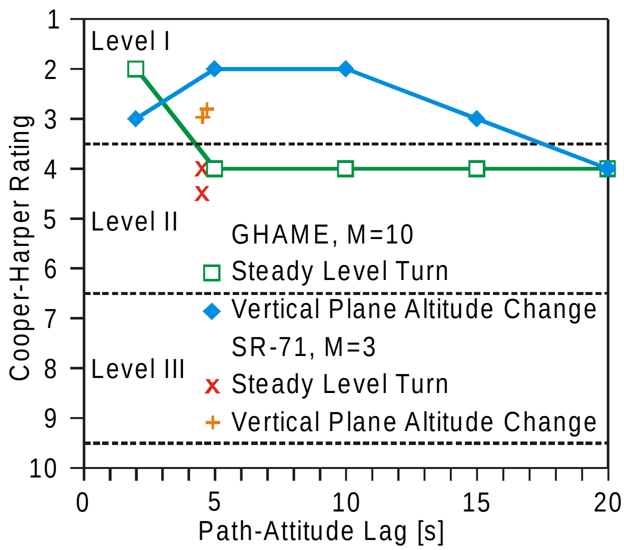

Fig. 10 Effect of path-attitude lag on pilot ratings for different maneuvers (GHAME model, M=10, h=110,000 ft)

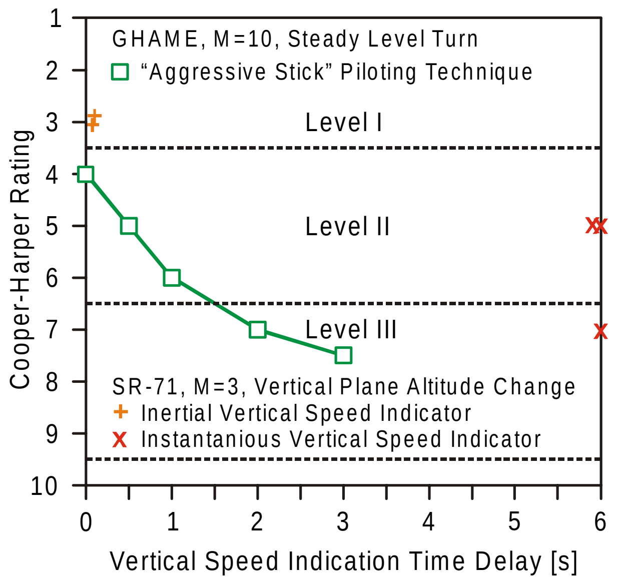

Fig. 11 Effect of time delay in the vertical speed indication on pilot ratings (GHAME model, *M*=10, *h*=110,000 ft)

Time Delay of Vertical Speed Information

Results concerning the effect of delayed indication of the vertical speed (diamond and linear vertical speed and acceleration scales) are shown in Fig. 11. There is a significant decrease in pilot rating with an increase in time delay. At higher values the pilot was only barely able to use the "aggressive stick" technique. Similar results have also been obtained with a SR-71 when the effect of an altimeter time lag has been evaluated (Fig. 11).

Scaling of the Diamond

Fig. 12 presents the effect of the diamond scale on handling qualities ratings for the basic simulation model at Mach 10 in 110,000 ft. In this case all eigenvalues are stable even tough the phugoid has a time to half amplitude of 46,740 seconds. There is no significant effect on handling qualities ratings (with a difference of 1 corresponding to normal scatter).

In the presence of a phugoid instability, there are significant changes (Fig. 13). For diamond scales with a resolution of less than 0.3 degrees pitch ladder per feet/second vertical speed the handling qualities rating gets worse and the pilot looses control. At values above this threshold, i.e. at a higher resolution, the rating remains constant. This holds for two different magnitudes of instability.

With respect to height mode instability there is not such an effect (Fig. 14). Only at diamond scales with higher sensitivity there is an deterioration of the handling qualities ratings.

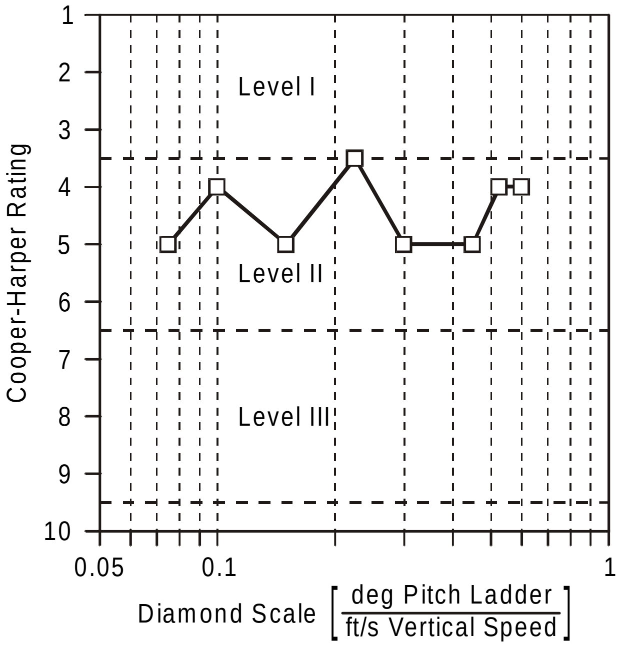

Fig. 12 Effect of different diamond scales on pilot ratings for basic GHAME model (*M*=10, *h*=110,000 ft)

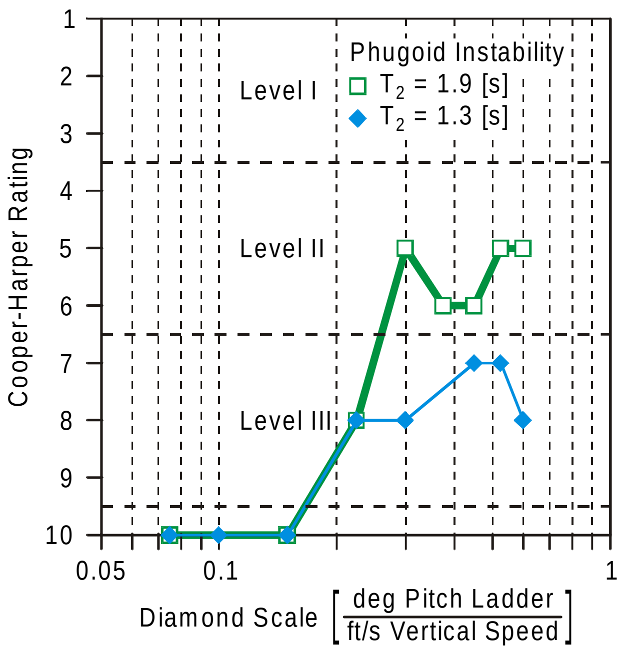

Fig. 13 Effect of different diamond scales on pilot ratings for phugoid instabilities (GHAME model, *M*=10, *h*=110,000 ft)

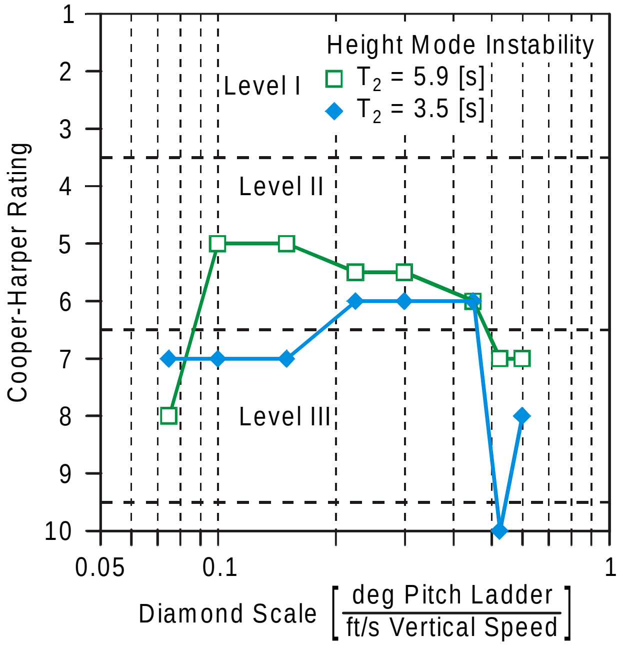

Fig. 14 Effect of different diamond scales on pilot ratings for height mode instabilities (GHAME model, M=10, h=110,000 ft)

6 Conclusions

In high speed flight, there is a large time lag between pitch attitude and flight path responses. It is shown that there is an upper limit for this path-attitude lag at a high level. This is due to the coupling of two real zeros in the pitch attitude transfer function to complex zeros.

A piloting technique ("aggressive stick") to overcome the flight path control problem related to the path-attitude lag by precise flight path angle or vertical speed tracking is described. This control technique also has an stabilizing effect on the phugoid.

Simulation experiments show that there is no effect of a path-attitude lag on handling qualities ratings when the "aggressive stick" technique is used. To utilize this piloting technique a precision vertical speed indication with appropriate scaling and without time lag is necessary. The simulator results are supported by similar results obtained from flight tests with a SR-71 research aircraft.

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